IDENTIFICATION FOR ROBUST CONTROL

(System Modeling for Synthesis of Control Laws)

Final Progress Report

(2nd year)

by

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One of the major theoretical contribution of our project is a new two-degree of freedom controller design approach based on a generic optimal control scheme. This is a new structure how to design optimal pole placement controllers. The scheme (named as a *generic* two-degree of freedom (*G2DF*) system) is based on a special (Keviczky-Bányász, or shortly *K-B*) parametrization. It was proved that the optimality of this scheme in H_2 and/or H_∞ spaces can be reached by special selection of two serial filters obtained from the solution of low order Diophantine equations and/or Navenlina-Pick approximation paradigm.

A new controller refinement technique was introduced which allows to determine the reachable maximum bandwidth under an amplitude constraint for the control action by iteratively redesigning the applied reference model as a new step in the basic iterative scheme.

It succeeded to derive a new uncertainty relationship limiting the product of control performance and robustness. In the generic scheme where the investigation was performed the control and identification errors are the same, so this inequality limits the product of the model accuracy and a robustness measure of the closed loop control system.

The different separate phases of identification for and design of robust control can properly be handled in a new approach combining the classical "minimum variance" like control with the a concept of "maximum variance" input design for robust identification for control. This "triple" control approach gradually (iteratively or recursively, depending on the applied scheme) improves the frequency spectrum of an initial reference input signal excitation approaching and concentrating on the vital medium frequency domain around the cross-over frequency.

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ABSTRACT

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KEYWORDS: System identification; process parameter estimation; optimal, robust and adaptive filtering and control; combined identification and control; identification for control.

INTRODUCTION

One of the most important areas of research in control theory is the design of feedback controllers for systems which have significant uncertainties in the plant. These uncertainties can result from a lack of precision in mathematical modeling of the plant and/or changes in the plant parameters with time. Two main techniques for design of controllers for systems with significant uncertainties are robust and adaptive control theories. System identification is an important tool in both techniques as well as in many other control design methods.

We finished the first year of an US ARO research project entitled "Identification for robust control", according to its time schedule and the *final report of the first year's activity* was submitted by June 30, 1995. Then a new proposal formulating the research program for the second year, where the planned activity is partly the organic continuation of the first year, was submitted and some new problems and tasks were also indicated. This proposal was accepted for 12 months with incremental funding for 12 more months and the research contract was signed on April 1, 1996, with a starting date of May 1, 1996. In the reported period we submitted three *Interim Reports* in due times (by July 31, October 30, 1996 and January 31, 1997) and this material is the *Final Report* of the second project year. The explanation of the considerable delay is very simple but interesting. We had quite nice scientific achievements, our results were accepted and we thought everything went very smoothly. Then we received a letter (dated October 8, 1996) from Gerald J. Iafrate, director, warning that ARO is suffering from drastic budget reductions so it might happen that ARO have to reduce or eliminate selected on-going research agreements. In my respond I asked him not to cut the foreign projects first because they are very few and small and it is against the official declarations we hear here from US politicians, embassy and visitors from NATO and the Pentagon. After a long correspondence with the administration (Angela Potter at the Office of Naval Research) and with the great help of Dr. Bushnell we received some payments (by November 8, December 3, 1996 and March 12, 1997) and not all, even if it did not fit to the scheduled dates (May 1, July 31, October 30, 1996 and January 31, 1997).

Meanwhile, in January, 1997 Mrs. Anita K Jones from the Pentagon visited our institute and we also reported her about our project. She was very satisfied with our research projects and she initiated some others with different groups of our institute and promised the continuation of the financial support.

Then in March, just before the closing date of the first year we received an e-mail from Dr. Bushnell that our project is not financed in the future because of the ARO's

drastic budget cut (no instruction how to proceed and to finish). The policy probably was to hang up first the foreign projects. It was a pity, because it was against all the previous statements and declarations and because there was practically no scientific evaluation on the results, which were, anyway, very well accepted everywhere in our international scientific community. Another demoralizing fact was, that the informing letter on the hang up was only an e-mail, which is very far from the very serious and demanding ARO formalities in the preparation and sign of contracts. What we could do: we had to accept the situation with regret and continue the research but stop the communication with ARO. We did not think that we should still submit a final report, when we had not received all payments contrary to the signed contract. To tell the truth we have participated in several other international projects of ten or hundred scale larger than this one and have never met such handling of the contracted scientists. This is a pity, because ARO, NAVY and other US offices (together with the NSF, NIH, etc.) played very positive role in the transformation of the former CEE countries.

Unexpectedly we received an e-mail and letter from Ms Mary N. Jackson (Procurement Technician) dated October 2, 1998 concerning the final report of our project with ARO due by July 31, 1997. In our respond we indicated, that we need a certain time to complete the *Final Report* of the second year, because we thought that our contract was suspended by ARO and promised to send it by the end of January, 1999.

PROJECT SUMMARY

We try to summarize the research achievements of our project obtained in the given period in different scientific topics. These major areas are the following

- generic optimal control system structure
  - iterative controller refinement
  - influence of the amplitude constraints of the control action for the reachable maximum bandwidth
  - triple control: simultaneous identification, optimal input design and control
  - interplay between identification performance and control robustness
- robust control, identification and filter design
  - robust control
  - approximate identification for control
  - robust filter design
  - special parameter estimation method

The generic optimal control system structure

A wide class of control problems can be properly handled in the framework of the so-called two-degree of freedom feedforward/feedback closed-loop control systems, having many variants published since the classical works. We believe that one of the major theoretical contribution of our project is a new regulator design approach based on a generic optimal control scheme developed by us. This is a new structure how to design optimal pole placement controllers. The scheme (which was later named as a *generic* two-degree of freedom (*G2DF*) system) is based on a special (Keviczky-Bányász, or shortly *K-B*) parametrization [1], [8].

It was proved that the special structure of the regulator in the generic scheme provides a family of realizable stabilizing controllers. Its optimality in H_2 and/or H_∞ spaces can be reached by special selection of two serial filters obtained from the solution of low order Diophantine equations and/or Navenlina-Pick approximation paradigm [27], [29], [30].

This generic structure opens a new way to handle system uncertainties, furthermore combined modeling and control issues providing a new canonical sensitivity scheme [10], [18]. It was shown that this iterative scheme maximizes a robustness measure, too. A new uncertainty relationship is introduced limiting the product of control performance and robustness. This new inequality family opens a possible future new way to quantitatively analyze inverse relationship between control performance and

robustness instead of the formerly known general qualitative dependence [2], [17].

Short summary of the most important advantages

- *generic*, clear structure and design requirements, minimal representations and gradual building of complexity,
- optimization by two factors: G_r, G_w in H_2- and/or H_∞-norm space,
- solutions of two "low order" Diophantine equations and/or Navenlina-Pick approximation paradigm,
- reasonable robust stability condition depending on the design goal only,
- an easy scheme for iterative controller refinement, avoiding identification in closed-loop,
- control and identification errors are the same with appropriate frequency weights,
- simple error equation representing the different contributions,
- simple convergence equations and nice properties,
- optimal regulator sensitivity minimizing the controller variance,
- the iterative scheme maximizes the simple geometric robustness measure,
- this is the only scheme where modeling (not control!!!) performance and robustness can be connected into a limiting product inequality.

Iterative controller refinement

The first visible advantage of the presented new *generic* controller scheme is that it gives a clear evolving structure how to obtain the optimal controller in a step by step reasonable way. An additional advantage that it is easy to construct an iterative controller refinement scheme based on the *G2DF* structure. It is possible to form an off-line [1], [8] ("batch") or on-line [8], [31] ("adaptive") version of the controller refinement algorithm. In this refinement scheme the "*closed-loop*" identification should be done between an auxiliary "*input*" signal and the controlled variable (output of the closed-loop) without opening the loop, because the *K-B* parametrization virtually opens the closed-loop in case of convergence.

Influence of the amplitude constraints of the control action for the reachable maximum bandwidth

The generic controller structure provided a very effective iterative controller refinement scheme, assuming no amplitude constraints for the control action signal as

usual at theoretical optimal regulator design methods. However, in the control engineering practice one should always assume a nonlinear limiter, corresponding to a real actuator. We proposed a special approach capable to handle the so-called power-surplus or amplitude constraints existing at most of the industrial or practical realizations of optimal control algorithms [3], [22].

A new controller refinement technique was introduced which allows to determine the reachable maximum bandwidth under an amplitude constraint for the control action by iteratively redesigning the applied reference model as a new step in the basic iterative scheme. The obtained new procedure fulfills the requirements of practical control engineers, too. The practical solution is the introduction of a new supervisory controller layer iteratively redesigning the applied reference model [16], [19].

It was shown how a real nonlinear actuator limiting the amplitude of the control signal influences the control performances. A special modification of the original iterative scheme was introduced, which allows the user to find the reachable maximal bandwidth by an iterative redesigning the original not reachable requirements, given by a first order reference model [4], [13], [14], [21].

The experience obtained here could be used for adaptive tuning of simple (e.g., *PID*) regulators [32].

Triple control: simultaneous identification, optimal input design and control

On the basis of the generic controller structure we formulated a special framework, where the different separate phase of identification for and design of robust control can properly be handled. This approach combines the classical "minimum variance" like control with the a concept of "maximum variance" input design for robust identification for control. In the first interim phase of the project this idea was only a conjecture. Using the MATLAB *CSILLA*™ package (developed during the first year) we could prove the nice converging properties of the new "maximum variance" reference input design algorithm [5]. This method works well both in the iterative off-line and adaptive on-line situation, too. The very interesting and effective feature of this method is that it gradually (iteratively or recursively, depending on the applied scheme) improves the frequency spectrum of an initial reference input signal excitation approaching and concentrating on the vital medium frequency domain around the cross-over frequency. This seems to be a natural way to solve the well known problem of "catch of 22" in combined identification and control paradigms, when one should know the process to generate the optimal excitation or to have *apriori* or "god given" frequency dependence of modeling error sensitivities. This new principle for optimal reference input design

outlines a new scheme of "triple-control", which is a special possible extension of the classical "dual-control" scheme - based on the simultaneous identification and control loops - with a third loop for optimizing the excitation [5]. Several different combinations of these loops can be imagined worth studying in the near future.

Interplay between identification performance and control robustness

The classical control literature is full of papers dealing with the interplay between control performance and control robustness. In the generic controller structure the modeling (identification) error and the control error are the same. This gave the special platform developing new relationships between modeling performance and control robustness [2], [28].

We found new uncertainty relationships limiting the product of control performance and robustness. This inequalities are probably not really surprising, however, in our generic scheme where the investigation was performed the control and identification errors are the same, so the derived inequality limits the product of the model accuracy and a robustness measure of the closed loop control system, which relationship seems to be quite new [18], [20], [23], [26].

The special limiting product inequality involves to study the saddle point of a saddle surface, laying on another hyperbolic surface. Special 3D graphics are necessary to give a better insight and to help understanding these sophisticated nonlinear relationships. These investigations required a lot of programming work.

Robust control, identification and filter design

Robust control

We introduced a new interpretation of H_∞ criteria in frequency domain. This interpretation gives special "butterfly" sensitivity (or robustness) shaping regions that can easily be applied on the classical Bode plot design techniques [6]. This interpretation seems to be very useful to handle the critical medium frequency domain in combined or simultaneous identification and control problems.

Approximate identification for robust control

In order to develop identification algorithms that are capable to provide an approximate model with a guaranteed H_∞ error bound, we considered a family of the algorithms elaborated for H_∞ identification called two-stage methods. The first step in these algorithms is usually a linear L_∞ approximation and the second step is a rational approximation from the space H_∞. This way the final rational model is obtained usually by solving a Nehari-approximation problem.

Linear approximation algorithms proposed in the literature so far, are merely based on the weighted partial sums of the trigonometric series of the system transfer function. These coefficients are obtained from the inverse Fourier-transform of the noisy frequency response data generated by a system with a transfer function that belongs to the disc algebra.

It can be seen that this approach has two design parameters: the choice of the weighting or window functions and the choice of the basis like trigonometric, Laguerre, Kautz or other generalized orthogonal basis.

We studied the effect of choosing a specific window function on the bound of the approximation error and on the convergence rate. A class of algorithms based on the so called φ-summation was elaborated to obtain approximate models from frequency domain data. This class of algorithms includes the formerly proposed windowing or summation approaches like the Fejér or the de la Vallée-Poussin summations as special cases. Further research was needed to consider the use of specific basis functions and to analyze their effect on the approximation error.

The results obtained for applying Laguerre-basis in H_2 identification to get algorithms for approximate identification under H_∞ criteria are generalized in [R2]. The approximate model is a truncated Laguerre expansion of the system transfer function. To ensure convergence in H_∞ norm, the idea of φ-summation (a generalization of Fejér or Cesaro summation) is applied. Besides the theoretical results, simulation examples are shown to illustrate that this idea can be generalized to obtain a new class of linear algorithms for use in H_∞ approximate identification .

The above research results opened new possibilities for further international scientific co-operations [33].

Robust filter design

A new robust detection filter using H_∞ filtering was developed which can be used in the presence of time varying system perturbations. The applied method is based upon a

Lie-algebraic approach to handle a wide class of possible disturbances in the system parameters [11], [15], [24], [25].

Special parameter estimation method

Most of the identification and parameter estimation methods used in robust control techniques are basically the different versions of the simple Least Squares (LS) algorithms. The solutions depend on the applied noise-model, model structure and in cases nonlinear-in-parameters, on the loss function minimization techniques, as well. We started the investigation of a possible generalization of these methods to try to find algorithms which could be simpler or better in providing analysis techniques for model uncertainty estimation and handling. Our first effort has been directed to process parameter estimation methods using template functions [7] and [R1]. The system is described by a stochastic difference equation, while the integrated values of the output are observed by different sensors at discrete times. The so-called extended template function estimator is developed on the basis of the conjugate equation theory. Under some weak conditions the parameter estimates obtained by the proposed method are asymptotically Gaussian distributed. It is shown that the covariance matrix of this distribution can be optimized with respect to the vector of template functions and that an optimal vector of template functions really does exist. With the optimal choice of the template function vector, the proposed estimator will give the same accuracy as the optimal instrumental variable estimator. When implementing the optimal template function method, a multistep algorithm consisting of four simple steps is proposed to estimate the system parameters and the parameters describing the noise characteristics.

PUBLICATIONS

In the list of publications our papers published in the project period 1996-1997 are presented. Those papers from our publications in 1998 which had been prepared and influenced by the project are also shown additionally.

Interim reports:

[R1] Keviczky, L. and Pham Huy Thoa (1996). System parameter estimation methods using template functions.

[R2] Bokor, J., L. Keviczky and F. Schipp (1996). Approximation by discrete Laguerre functions in H_∞ norm.

Publications:

[1] Keviczky L. and Cs. Bányász (1995). A new pole-placement regulator design method. *34th IEEE CDC*, New Orleans, Lousiana, USA, 3408-3413.

[2] Keviczky, L. and Cs. Bányász (1996). On the dialectics of identification and control in iterative learning schemes (A Heisenberg-type uncertainty law in combined identification and control). *DYCOMANS Workshop*, Algarve, Portugal, 77-82.

[3] Keviczky, L. and Cs. Bányász (1996). A new iterative controller refinement technique for amplitude constrained control action. *2nd World Automation Congress, WAC'96*, Montpellier, France, TSI Press Series, Robotic and Manufacturing Systems, Vol. 3, 369-376.

[4] Keviczky, L. and Cs. Bányász (1996). An iterative regulator refinement scheme finding the optimal reachable bandwidth for nonlinear actuators with limited control action (Tutorial), *EURACO Summer Workshop*, Algarve, Portugal, 71-82.

[5] Keviczky, L. and Cs. Bányász (1996). Extension of dual control: the concept of triple control. *IFAC World Congress*, San Francisco, USA, Vol. K., 265-270.

[6] Bányász, Cs. and L. Keviczky (1996). H_∞ criteria in frequency domain. *2nd World Automation Congress, WAC'96*, Montpellier, France, TSI Press Series, Vol. 4, 41-48.

[7] Keviczky, L. and P. H. Thoa (1996). Identification techniques for correlated noise systems with multisensors. *IEEE Instrumentation/Measurement Technology Conference, IMTC'96, I3C: Integrating Intelligent Instrumentation & Control,* Brussels, Belgium, 306-311.

[8] Keviczky, L. (1996). Combined identification and control: another way, *IFAC Journal Control Engineering Practice,* **4**, 5, 685-698.

[9] Keviczky, L. (1996) Modern Control Theory with Application Aspects to Intelligent Vehicle Systems, *IAVSD'97 Miniconf,* Budapest.

[10] Keviczky L. and Cs. Bányász (1996). On the dialectics of identification and control in iterative learning schemes (A Heisenberg-type uncertainty law in combined identification and control). *ESF-COSY 2nd Joint Workshop*, Valencia, Spain.

[11] Keviczky L. (1996). Modern control theory with application aspects to intelligent vehicle systems. *6th Mini Conference on Vehicle Systems Dynamics, Identification and Anomalies VSDIA'96*, Budapest, Hungary.

[12] Bokor J. (1996). Robust detection filter design using H_∞ filtering. *6th Mini Conference on Vehicle Systems Dynamics, Identification and Anomalies VSDIA'96,* Budapest, Hungary.

[13] Keviczky L. and Cs. Bányász (1997). An iterative regulator refinement scheme finding the optimal reachable bandwidth with limited control action. *Control of Nonlinear & Uncertain Systems, ESF-COSY Workshop*, Zürich, Switzerland.

[14] Keviczky, L. and Cs. Bányász (1997). An iterative reference model redesign technique for intelligent regulator tuners, *2nd IIGSS Workshop, San Marcos, TX, USA, In: Advances in Systems Science & Applications, An Official Journal of the International Institute for General Systems Studies, Eds: Y. Lin and Y. Ma*, 87-100.

[15] Edelmayer, A., J. Bokor, F. Szigeti and L. Keviczky (1997). Robust detection filter design in the presence of time varying system perturbations, *IFAC J. Automatica*, 33,3,471-475.

[16] Keviczky L. and Cs. Bányász (1997). How to combine practical needs of control engineers with advanced iterative controller refinement? *3rd Symp. on Intelligent Components and Instruments for Control Applications SICICA'97*, Annecy, France, 223-230.

[17] Bányász Cs. and L. Keviczky (1997). Convergence and robustness properties of a generic regulator refinement scheme. *2nd IFAC Symposium on Robust Control Design ROCOND'97*, Budapest, Hungary, 495-500.

[18] Keviczky L. and Cs. Bányász (1997). Interplay between robustness versus control and identification performances. *2nd IFAC Symposium on Robust Control Design ROCOND'97,* Budapest, Hungary, 367-374.

[19] Keviczky L. and Cs. Bányász (1997). Influence of amplitude constraints: an iterative redesign technique of reference models. *European Control Conference*

ECC'97, Brussels, Belgium, TH-M-F1.

[20] Bányász Cs. and L. Keviczky (1997). Limiting robustness properties in an iterative identification and control scheme. *11th IFAC Symposium on System Identification SYSID'97*, Fukuoka, Japan, 601-606.

[21] Keviczky L. and Cs. Bányász (1997). An iterative redesign technique of reference models: how to reach the maximal bandwidth? *11th IFAC Symposium on System Identification SYSID'97*, Fukuoka, Japan, 619-624.

[22] Bányász, Cs. and L. Keviczky (1997). Influence of amplitude constraints: an iterative redesign technique of reference model. *ESF COSY Workshop on Control of Nonlinear and Uncertain Systems*, Zurich, Switzerland, 68-79.

[23] Bányász, Cs. and L. Keviczky (1997). New robustness properties of an iterative controller refinement scheme, *IASTED Symp Modeling, Identification and Control MIC'97*, Innsbruck, Austria, 313-318.

[24] Edelmayer, A., J. Bokor, L. Keviczky (1997). Improving sensitivity of H_∞ detection filters in linear systems. *11th IFAC Symposium on System Identification SYSID'97*, Fukuoka, Japan, 1195-1200.

[25] Edelmayer, A., J. Bokor and L. Keviczky (1997). A scaled L_2 optimization approach for improving sensitivity of H_∞ detection filters for LTV systems. *2nd IFAC Symposium on Robust Control Design ROCOND'97*, Budapest, Hungary, 543-548.

[26] Keviczky, L. and Cs. Bányász (1997). Robustness and reachable bandwidth versus control and identification performances. *2nd IFAC Workshop on New Trends in Design of Control Systems, NTDCS'97*, Smolenice, Slovakia, 89-95.

[27] Keviczky, L. and Cs. Bányász (1997). A generic optimal two-degree of freedom controller scheme: identification and control paradigms, *ESF 3rd Joint COSY Workshop*, Budapest, Hungary, 201-214.

1998

[28] Keviczky, L. and Cs. Bányász (1998). Dialectics of identification and control: product inequalities in an iterative scheme. *Proc. of World Automation Congress (WAC'98) ISIAC'98*, Anchorage, Alaska, *TSI Series, Intelligent Automation and Control, Recent Trends in Development and Applications,* (Eds: M. Jamshidi, C.W.de Silva), Vol. 6., 169-176.

[29] Bányász, Cs. and L. Keviczky (1998). Designing high performance two-degree of freedom controllers. *Instrumentation and Measurement Technology Conference IMTC'98*, St. Paul, MN, USA, 1359-1366.

[30] Keviczky, L. and Cs. Bányász (1998). Optimal two-degree of freedom controllers: Iterative refinement, robustness and error properties. *American Control Conference*, Philadelphia, PA, USA, Vol. 1, 188-189.

[31] Bányász, Cs. and L. Keviczky (1998). An adaptive two-degree of freedom controller. *IFAC Workshop on Adaptive Control and Signal Processing, ACASP'98*, Glasgow, UK, 34-39.

[32] Bányász, Cs. and L. Keviczky (1998). A simple adaptive PID tuner. *IFAC Conference on System Structure and Control*, Nantes, France, Vol. 2, 493-499.

[33] Heuberger, P.S.C., Z. Szabó, T.J. de Hoog, P.M.J. Van den Hof and J. Bokor (1998). Realization algorithms for expansions in generalized orthonormal basis functions. *Selected Topics in Identification, Modeling and Control*, Vol.11, 61-68.

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